Improving Earthquake Locations in Northern California Using Waveform Based Differential Time Measurements

Grant 05HQGR0051

Felix Waldhauser and David Schaff

Lamont-Doherty Earth Observatory of Columbia University, Palisades, NY 10964

Tel: (845) 365 8538; Fax: (845) 365 8150; felixw@ldeo.columbia.edu

URL: http://www.ldeo.columbia.edu/~felixw

NEHRP Element III

Keywords: Source characteristics, Seismotectonics, Database

Annual Project Summary for FY 2005

This report covers the activities performed between January 1, 2005 (start date of the project) and October 31, 2005 of this one-year project. The work described in this report is being undertaken by the principle investigator Felix Waldhauser and by co-PI David Schaff. The research includes the quality assessment of a recently developed comprehensive waveform cross-correlation database, and its use to relocate the entire NCSN earthquake catalog using the double-difference method.

1. Investigations undertaken

Assessment of cross correlation data accuracy

We have assessed the quality of a recently computed database of cross correlation delay time measurements for Northern California (USGS/NEHRP grant 03HQGR0004; Schaff and Waldhauser, 2005) (Figure 1). The measurements are based on the complete waveform database (up to May 2003) stored at the Northern California Earthquake Data Center (NCEDC) at the University of Berkeley. 23 billion cross correlations were performed on pairs of seismograms recorded at common stations from pairs of events that are separated by less than 5 km. 1.7 billion P-wave and 1.2 billion S-wave differential times were obtained from pairs of seismograms that had cross correlation coefficients of 0.6 or larger. In addition to the cross correlation data we have computed approximately 1 billion travel time differences from P-phase picks listed in the earthquake bulletin of the Northern California Seismic Network (NCSN).

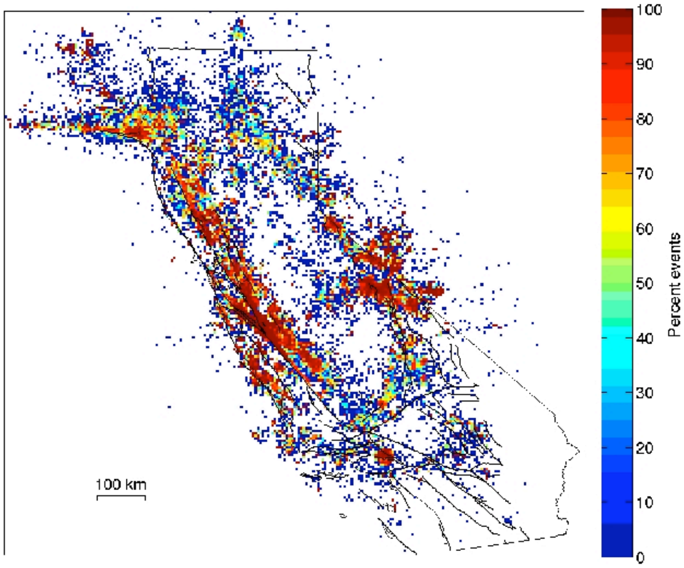

Figure 1 Percentage of correlated events that have cross-correlation coefficients of CC ≥0.7 with at least one other event recorded at four or more stations. Percentages are computed from the total number of events within bins of 5x5 km

Before using the new differential-time data for relocation purposes we assessed their accuracy by comparing them to cross correlation measurements made independently by Peter Shearer (pers. comm.) for earthquakes recorded at 470 NCSN stations near Mendocino, northern California. Both our (Schaff et al., 2004) and Shearer's (Hauksson and Shearer, 2005) method use a time-domain cross-correlation function, but employ different interpolation functions and cross correlation parameters (e.g., window lengths, lags). Histograms of the differences between the two sets of differential times are shown in Figure 2 for events common in both data sets. From a total of 32,475 differential times compared, 96% of the P-wave data agree within 10 msec, and 63% within 1 msec (Figure 2a). 92% of the S-wave data agree within 10 msec, 59% within 1 msec (Figure 2b). Most differences between the two sets are smaller than the sampling rate (100 Hz). Outliers are sparse, and present in both data sets. They are likely caused by glitches during the cross correlation process such as cycle skipping or correlation of noise. Prior to using our data for relocation we detect outliers by comparing time measurements made for both 1 and 2 sec windows. Measurements with differences larger than one sample are typically removed. Correlated noise, for example, can be easily detected this way.

Histograms of differences in cross correlation coefficients are shown in Figure 2a and b for P-waves and S-waves respectively. Cross-correlation coefficients tend to be systematically higher for our measurements compared to those by Shearer. This is likely due to the different window lengths used by the two groups. Even though we computed both 1 and 2 sec windows for the NCSN data, only cross correlations over 1 sec window lengths are analyzed here. We typically use the 1 sec window length data for relocation purposes. Shearer computes the cross correlation function for window lengths of 2 and 3 seconds around the P-wave and S-wave train, respectively.

A comparison of our cross correlation data with the corresponding travel-time differences formed from NCSN phase picks (Figure 2e) indicates a standard deviation of 150 msec, which is similar to the assumed pick accuracy for P-phases. S-phases are not routinely picked at the NCSN.

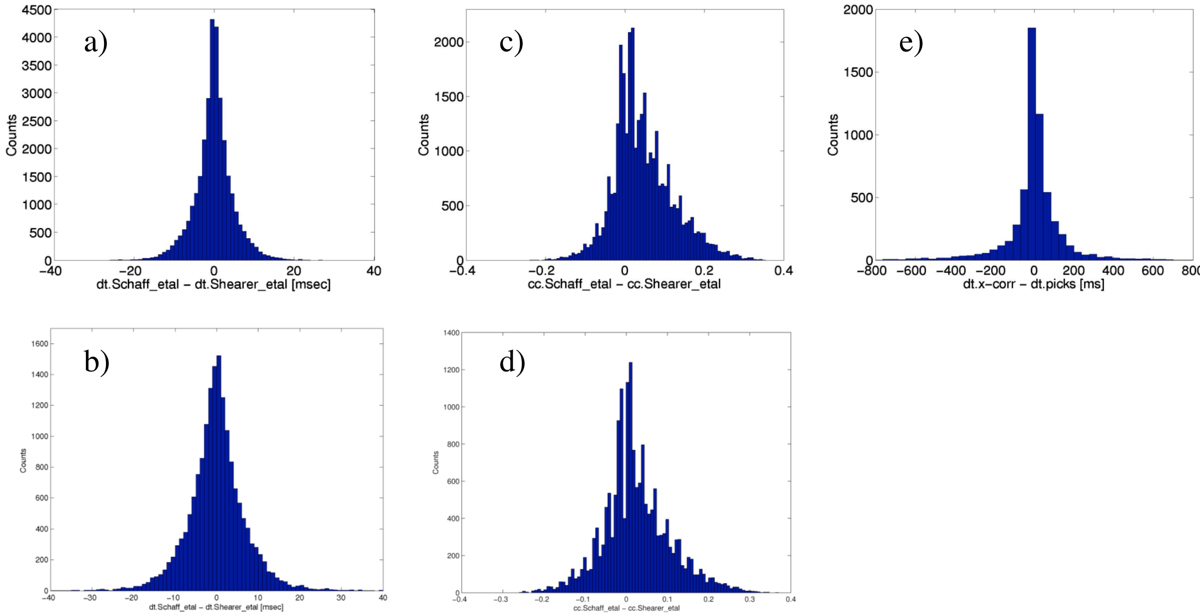

Figure 2 Histograms of differences between cross correlation measurements computed by Schaff and Waldhauser (2005) and P. Shearer (pers. comm.) for earthquakes near Mendocino, CA. a) P-delay times. b) S-delay times. c) P-wave cross correlation coefficients. d) S-wave coefficients. e) Differences between our cross correlation P-wave delay times and delay times formed from the NCSN phase picks.

Work to adapt hypoDD for large-scale event relocation

We have used the cross correlation and phase pick data together with an improved version of the *hypoDD* software (Waldhauser, 2001) to relocate the entire catalog of the NCSN. Improvements to the *hypoDD* software include the ability to use a variety of models (1D, 3D, and station specific models) to predict travel-time differences and partial derivatives, an improved weighting scheme, and features that help automat the choice of relocation parameters. *HypoDD* has been transported to a 16 node Linux cluster at Lamont to scope with the vast amount of data. The relocation problem has been regionalized to distribute the computational load to individual processors. The program now runs in a black box mode in which the best relocation parameters are found automatically.

We investigated the effect that the 3D velocity structure has on 1D double-difference solutions. We used the Parkfield differential-time data set described in Waldhauser et al. (2004) together with a recently derived 3D model for the Parkfield area (Thurber et al., 2006) to obtain 3D *hypoDD* solutions and compared them to DD solutions obtained with a 1D layered velocity model (essentially those described in Waldhauser et al. 2004). Figure 3 shows the difference between the two results, in map view and cross section. Note that some of the discrepancies (red lines) appear to be caused by numerical instabilities in the 3D ray tracing routine, and further investigations are necessary to solve these problems. The mean in absolute horizontal shifts between the two sets of locations is 140 m, and 180 m in vertical direction. The mean in relative location differences between each event and its neighbors within 2 km is only 33 m. These results indicate that good 1D velocity model are a very efficient way to relocate earthquakes even in areas as structurally complex as the Parkfield section of the San Andreas fault. We will investigate the use of a recently developed 3D velocity model for all of northern California (Tom Brocher, pers. comm.) as well as local-scale models for relocation purposes.

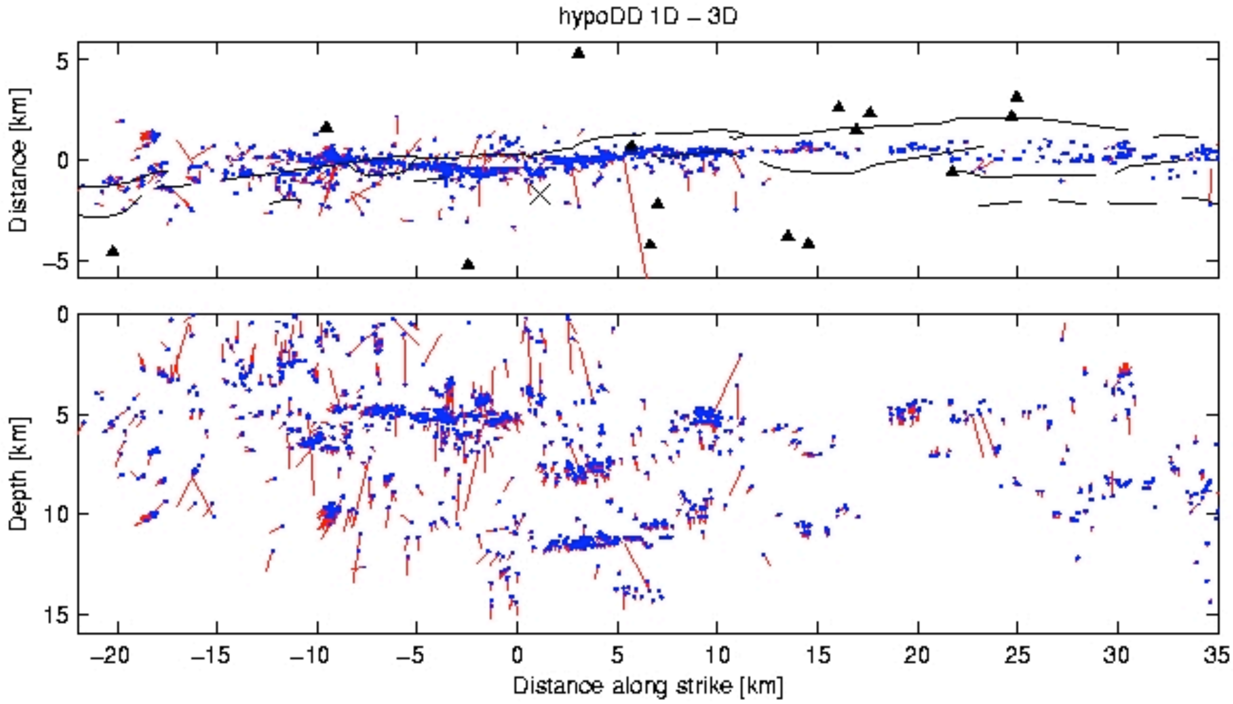

Figure 3 Comparison between 1D and 3D double-difference solutions. Top panel: Map view. Bottom panel: NW-SE cross-section. Blue dots: hypoDD locations obtained in a1D layered velocity model (Waldhauser et al. 2004). Red lines point to the corresponding hypoDD locations obtained by ray tracing in a 3D velocity model.

2. Preliminary Relocation Results

Preliminary results from relocating 350,000 events in the NCSN catalog indicate substantial improvement in event locations across all of Northern California. Even in complex tectonic areas such as at the intersection of the San Andreas and Calaveras faults the double-difference locations produce a sharp image of the seismicity (Figure 4). In addition, artifacts in the NCSN locations, most likely caused by effects related to transitions in regional 1D models used for routine locations, are removed. The average hypocenter shift between NCSN and DD locations is about 1.6 km. In depth the shift is 0.9 km. These values are somewhat smaller than the formal uncertainty associated with the routine locations (1.0 km in horizontal and 1.9 in vertical direction).

We are in the process of verifying the new DD locations with known locations of quary blasts (Brocher, 2003). These ground truth locations help us to assess the location accuracy of some of the most difficult events to relocate, the ones of small shallow events.

Initial investigations into the existence of repeating events in areas other than strike slip faults indicate that they occur abundantly in other tectonic regimes such as the Long Valley Caldera and the Mendocino triple junction.

Work in collaboration with David Oppenheimer and staff at the NCSN has been initiated to implement the waveform cross correlation and double-difference algorithm into the real-time earthquake catalog production procedure at the NCSN.

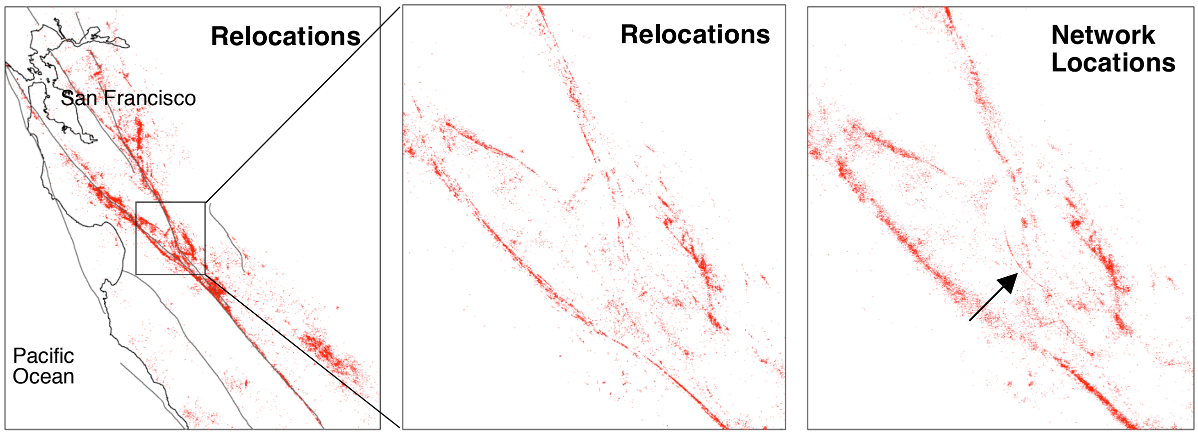

Figure 4 Waveform based double-difference relocations. Zoom into a tectonically complex area where the Calaveras fault joins the San Andreas fault. A much sharper picture of the seismicity emerges from the relocated data, indicating that the degree of resolution obtained in recent, small-scale relocation studies can be obtained for large areas and across complex tectonic regions. Artifacts in the routine locations such as the arch like feature (see arrow in above figure) are removed after relocation.

Improving Earthquake Locations in Northern California Using Waveform Based Differential Time Measurements

Grant 05HQGR0051

Felix Waldhauser and David Schaff

Lamont-Doherty Earth Observatory of Columbia University, Palisades, NY 10964

Tel: (845) 365 8538; Fax: (845) 365 8150; felixw@ldeo.columbia.edu

URL: http://www.ldeo.columbia.edu/~felixw

NEHRP Element III

Keywords: Source characteristics, Seismotectonics, Database

3. Non-technical Summary

We use a recently developed cross-correlation differential-time data base to relocate all seismic events recorded at the Northern California Seismic Network (NCSN) using the double-difference method. The data base provides differential travel times for similar earthquakes that are an order of magnitude more precise than what is obtained from phase picks. Initial relocation results for about 350,000 earthquakes indicate substantial improvements in hypocenter locations across large areas, and various tectonic enviornments. The average difference between the original NCSN locations and the double-difference relocations is about 1.6 km. The new high-resolution double-difference catalog, when completed, will provide the fundamental data for further studies on earthquake occurrence and interaction, earth structure, and seismic hazard assessment.

4. Reports published (related to this project)

Schaff, D. and F. Waldhauser, Waveform Cross Correlation Based Differential Travel Time Measurements at the Northern California Seismic Network, *BSSA*, 2005, in press.

Waldhauser, F. and D.P. Schaff, Regional-scale Seismic Event Relocation in Northern California, Eos Trans. AGU, 86(52), Fall Meet Suppl., Abstract S53C-06, 2005.

Hardebeck, J. L., F. Waldhauser, A. Michael, and W. L. Ellsworth, Parkfield earthquake locations: implications for structure and fault mechanics, SSA Annual Meeting, Lake Tahoe, *Seism. Res. Lett.*, 76, 2005.

Richards, P. G., W.-Y. Kim, F. Waldhauser, D. P. Schaff, What Fraction of Seismicity Can Be Located Using Cross-correlation and Multiple-event Relocation Algorithms? SSA Annual Meeting, Lake Tahoe, *Seism. Res. Lett.,* 76, 2005.

Waldhauser, F. and D. Schaff, Progress in Waveform Based Wide Area Event Relocation in Northern California, Proceedings and Abstracts, Volume XV, Southern California Earthquake Center Annual Meeting, Palm Springs, CA, September, 2005.

5. References

Brocher, T. M., Hypocentral Accuracy of Surficial Detonations in Northern California, *Seism. Res. Lett.,* 74, 1, 2003.

Hauksson, E. and P. Shearer, Southern California Hypocenter Relocation with Waveform Cross-Correlation: Part 1. Results Using the Double-Difference Method, *BSSA,* 95, 896-903, 2005.

Schaff, D. P., G. Bokelmann, W. L. Ellsworth, E. Zanzerkia, F. Waldhauser, and G.C. Beroza, Optimizing correlation techniques for improved earthquake location, *Bull. Seism. Soc. Am.*, 94, 705-721, 2004.

Schaff, D. and F. Waldhauser, Waveform Cross Correlation Based Differential Travel Time Measurements at the Northern California Seismic Network, *BSSA*, 2005, in press.

Waldhauser, F., HypoDD: A computer program to compute double-difference hypocenter locations, *U.S. Geol. Surv. open-file report*, 01-113, Menlo Park, California, 2001.

Waldhauser, F. and W. L. Ellsworth, A double-difference earthquake location algorithm: Method and application to the northern Hayward fault, *Bull. Seism. Soc. Am.*, 90, 1353-1368, 2000.

6. Available Data

It is our goal to make the relocated catalog openly and publicly available after completion of this project.

For more information on data availability, contact:

Dr. Felix Waldhauser
Lamont-Doherty Earth Observatory
61 Route 9W
Palisades, NY 10964
felixw@ldeo.columbia.edu